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USE OF INTERNAL COOLANT AS A MEANS OF PERMITTING INCREASE IN ENGINE TAKE-OFF POWER

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RESTRICTED BULLETIN

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SUMMARY

Engine tests, together with estimates made at Langley Memorial Aeronautical Laboratory, indicate that a 25-percent increase in take-off power can be obtained with present-day aircraft engines without increasing either the knock limit of the fuel or the external cooling requirements of the engine. This increase in power with present fuels and present external cooling is made possible through the use of an internal coolant inducted through the inlet manifold. Estimates on aircraft indicate that this 25-percent increase in power will permit an approximate usable increase of 8.5 percent in the take-off load of existing military airplanes. This increase in load is equivalent to an increase in the weight of gasoline normally carried of between 30 and 65 percent.

INTRODUCTION

Internal cooling through the introduction of water or water-alcohol mixtures into the inlet charge has been tested at various laboratories. Pertinent references to this work are contained in reference 1.

It is generally recognized that, if the take-off power of current engines can be increased, the performance of the airplane, with particular emphasis on range, can be increased. Increase in take-off power with present engines is limited by three factors: (1) knock characteristics of the fuel, (2) engine strength, and (3) engine cooling.

The knock characteristics of the fuel can be improved only at the expense of fuel supply. Because of limitations of supplies, this procedure can only be used for small quantities of fuel, such as might be used during take-off.

The engine strength is limited by both the loads imposed within the engine and the temperatures that the engine parts can withstand. External cooling of the engine with higher take-off powers does not provide so effective a means of relieving the thermal stresses within the cylinder as does internal cooling.

Internal cylinder cooling by means of introducing an inert liquid to the incoming charge permits much higher powers to be taken from a given fuel without knock and without increasing the external cooling. Data obtained at Langley Memorial Aeronautical Laboratory during 1942 showed that the permissible indicated mean effective pressure can be increased 100 percent by means of internal cooling. This value is not meant to represent a practical goal but to emphasize the fact that through internal cooling the knock limit of present fuels can be placed well above present demands. Internal cooling removes engine cooling as a problem for increased take-off powers. The lower temperatures obtained with internal cooling also reduce the probability of engine failure through increased loads.

This analysis was made at Langley Memorial Aeronautical Laboratory, Langley Field, Va., in the spring of 1942.

ENGINE TESTS

Upon the completion of tests recorded in reference 1, Dr. R. F. Selden of the NACA staff suggested the use of a mixture of ammonia dissolved in water (ammonium hydroxide) for the internal coolant as a means of overcoming the difficulties resulting from the high freezing point of water. Ammonia is unique in that on a weight basis it permits a greater percentage of water in the coolant for a given freezing temperature than does any other known liquid. For example, a mixture of approximately 30 percent ammonia by weight and 70 percent water has a freezing point of -94° F. A 28-72 ratio of ammonia and water was used in the internal-coolant tests described in this report. By the use of this material a given freezing-temperature requirement is met with the largest possible percentage of water in the internal coolant.

The amount of freezing-point depressant required in the internal coolant is dependent on the particular installation used. The freezing-point requirements of the internal coolant are not necessarily the same as for the gasoline.

The consideration in this report of ammonium hydroxide for the internal coolant does not imply that it gives better cooling and better knock suppression than other internal coolants, such as water-alcohol. The decision as to which internal coolant is best must be considered on the basis of availability and ease of handling as well as on the basis of engine performance.

Preliminary tests conducted on the CFR engine gave results sufficiently encouraging to warrant transferring the work to a single-cylinder Wright G200 engine mounted on a CUE crankcase. Figure 1 shows that ammonium hydroxide actually was a better knock suppressor than was pure water. These data represent the preliminary tests, which show that as far as knock is concerned engines with present fuels can be taken to much higher power outputs than are now permitted.

The tests were continued on ammonium hydroxide rather than on water or water-alcohol mixtures in order to find out what deleterious effects ammonium hydroxide might have on the engine. (Ammonium hydroxide is quite corrosive to any materials containing copper.) In addition to fuel limitations, engine temperature was considered as a limiting factor, and a maximum allowable temperature of 325° F at the middle rear of the cylinder barrel was decided upon. In the tests at each fuel-air ratio for different quantities of internal coolant, the inlet pressure was increased until (1) the engine knocked, (2) preignition or afterfiring occurred, or (3) the temperature at the middle rear of the cylinder barrel exceeded 325° F.

The following engine conditions were maintained constant:

Engine speed, rpm	2500
Spark advance, deg B.T.C.	20
Compression ratio	7.0
Oil-in temperature, °F	180
Inlet-air temperature before introduction of either fuel or internal coolant, °F	250
Cooling-air pressure drop, in. water	10

Figure 2 presents the experimental data. Except for the lean and rich ends of the curves, the limitation was engine temperature rather than fuel knock. The fact that the specific fuel consumption in the rich regions increased as the amount of ammonium hydroxide was increased indicates that the effect of ammonium hydroxide in suppressing knock was twofold: (1) It provided internal cooling of combustion gases; and (2) it retarded the combustion, giving the same effect as a retarded spark.

Cross plots from the data in figure 2 are shown in figures 3 and 4. Engine temperatures are shown in figure 5. A reference value of 245 pounds per square inch indicated mean effective pressure, which corresponds to 210 pounds per square inch brake mean effective pressure at a mechanical efficiency of 86 percent, approximates current take-off conditions. The data in the upper half of figure 3 are based on this value of 245 pounds per square inch indicated mean effective pressure (reproduced in fig. 5) for comparing the increase in power recorded with the different quantities of the internal coolant.

With a 25-percent increase in power, the weight of the internal coolant required is 54 percent of the fuel weight at a fuel-air ratio of 0.09. Other values given in figures 3, 4, and 5 are as follows:

COMPARISON OF ENGINE PERFORMANCE WITHOUT AND WITH INTERNAL COOLANT

	Without internal coolant (take-off hp)	With internal coolant (1.25 X take-off hp)
Point designation on curves	B	A
Indicated mean effective pressure, lb/sq in.	245	306
Inlet pressure, in. Hg absolute	56	73
Fuel-air ratio	0.11	0.09
Indicated specific fuel consumption, lb/hp-hr	.72	.62
Indicated specific liquid consumption, lb/hp-hr	.72	.96
Temperature of cylinder barrel, middle rear, °F	320	320
Temperature of rear spark-plug bushing, °F	415	365
Temperature of exhaust-valve guide, °F	495	565

The required inlet pressure of 73 inches Hg absolute would probably require some additional boost to that supplied with a single-stage high-speed supercharger.

ESTIMATED INCREASE OF ENGINE PERFORMANCE THROUGH INCREASED TAKE-OFF POWER

Increased load. - Four airplanes of different classifications, designated A, B, C, and D in this paper, have been considered in estimating the increased performance through a 25-percent increase in take-off power. These airplanes with the operating characteristics used in the present calculations are listed as follows:

Airplane Type	Airplane Designation	Normal take-off horsepower	Normal fuel capacity (gal)	Normal fuel capacity (lb)	Gross weight of airplane (lb)	Engine
Heavy bomber	A	4800	1433	8598	41,000	R-1830
Pursuit	B	2000	210	1260	11,870	R-2800
Torpedo bomber	C	1700	301	1806	15,364	R-2600
Shipboard fighter	D	2000	344	2064	12,577	R-2800

Complete calculations for estimating the total weight of the internal coolant and the internal-coolant system are given in the appendix. The following table presents the estimated increases in usable load for the four airplanes under consideration with a 25-percent increase in take-off power. The estimates of percentage total-load increase were made by Mr. J. W. Wetmore of the Flight Research Division of Langley Memorial Aeronautical Laboratory.

In the calculations of the table an allowance of 0.78 pound of coolant per pound of fuel was used instead of the value of 0.54 shown on the curve at point A of figure 3. This increase is introduced as a factor of safety. All estimates are based on sufficient internal coolant for a 5-minute operation. The increase in propeller weight required for the additional power output is estimated to be 100 pounds, and the weight of the system for introducing the coolant, exclusive of the tank weight, is estimated to be 75 pounds. These weights are considered to be the same for each engine of the four airplanes listed.

ESTIMATED INCREASE IN TAKE-OFF LOAD FOR
25-PERCENT INCREASE IN TAKE-OFF POWER

Airplane	Load increase (percent)	Load increase (lb)	Usable load increase (lb)	Usable load (gal of gasoline) (a)	Percentage increase (gal of gasoline)
A	11.5	4710	3631	427	30
B	12.0	1430	1097	129	65
C	10.5	1610	1300	153	51
D	10.5	1320	1037	122	36

[a]Assume 1 gal gasoline weighs 6.0 lb; gasoline tank weighs 2.5 lb/gal; therefore, $\frac{3631}{8.5} = 427$ gal.

The data show that a 25-percent increase in take-off horsepower results in a marked increase in either the usable load or in this usable load translated into gallons of gasoline. The increase for airplanes B and D is particularly noteworthy.

Increased rate of climb. - It is estimated that a 25-percent increase in take-off power for airplane B will permit the rate of climb up to 12,000 feet to be increased from 3100 to 4100 feet per minute. Corresponding values for airplane C are from 1600 to 2200 feet per minute.

<u>Decreased take-off run</u>. - In regard to take-off run, for the assumed loading of the airplanes, it is estimated that a 25-percent increase in power will decrease the take-off runs of the four airplanes as follows:

Airplane	Present take-off distance (ft)	Take-off distance 25-percent increase in take-off power (ft)
A	1700	1300
B	1300	1000
C	300	200
D	350	250

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APPENDIX

COMPUTATIONS FOR WEIGHT REQUIREMENTS FOR INTERNAL-COOLING SYSTEM

From figures 3 and 4:

isfc at 245 imep = 0.72, fuel-air ratio = 0.11 (B)

isfc at 306 imep = 0.96, fuel-air ratio = 0.09 (A)

For R-2800 engine at 2700 rpm:

$$ihp_{245} = \frac{245 \times 2800 \times 2700}{7.92 \times 10^5} = 2340$$

At 85-percent mechanical efficiency, 2340 ihp = 2000 bhp, ihp_{306} = 2920, and bhp = 2500.

Assume sufficient ammonium-hydroxide solution (NH_4OH) for 5 minutes at 2500 bhp:

$$\text{bslc} = \frac{0.96}{0.85} = 1.13 \text{ lb/bhp-hr}$$

At 2000 bhp

$$\text{bsfc} = \frac{0.72}{0.85} = 0.85 \text{ lb/bhp-hr}$$

At 2500 bhp

$$\text{total liquid} = 2500 \times \frac{5}{60} \times 1.13 = 235 \text{ lb}$$

This 235 lb liquid is 152 lb of gasoline and 83 lb of ammonium-hydroxide solution.

At 2000 bhp

$$\text{total gasoline} = 2000 \times \frac{5}{60} \times 0.85 = 142 \text{ lb}$$

It is noted that increased weight of gasoline is negligible.

Density of NH_4OH = 7.5 lb/gal

70 lb NH_4OH = 9.4 gal

Allow for 15 gal, or 113 lb, NH_4OH

Assume tank for NH_4OH weighs 35 lb

Total weight = 113 + 35 + 10 (for extra gasoline) = 158 lb = W_1

Assume this weight requirement is proportional to bhp of engine.

Let increased propeller weight = 100 lb

Let weight of coolant-induction system = 75 lb

175 lb = W_2

Assume W_2 constant for engines considered.

Engine	1.25 x take-off horsepower	W_1 (lb)	W_2 (lb)	$W_1 + W_2$ (lb)
R-2800	2500	158	175	333
R-2600	2130	135	175	310
Four R-1830	6000	379	700	1079

Final calculations on usable load are given in the third table in the text.

REFERENCE

1. Rothrock, Addison M., Krsek, Alois, Jr., and Jones, Anthony W.: Summary Report on the Induction of Water to the Inlet Air as a Means of Internal Cooling in Aircraft Engine Cylinders. NACA ARR, Aug. 1942.

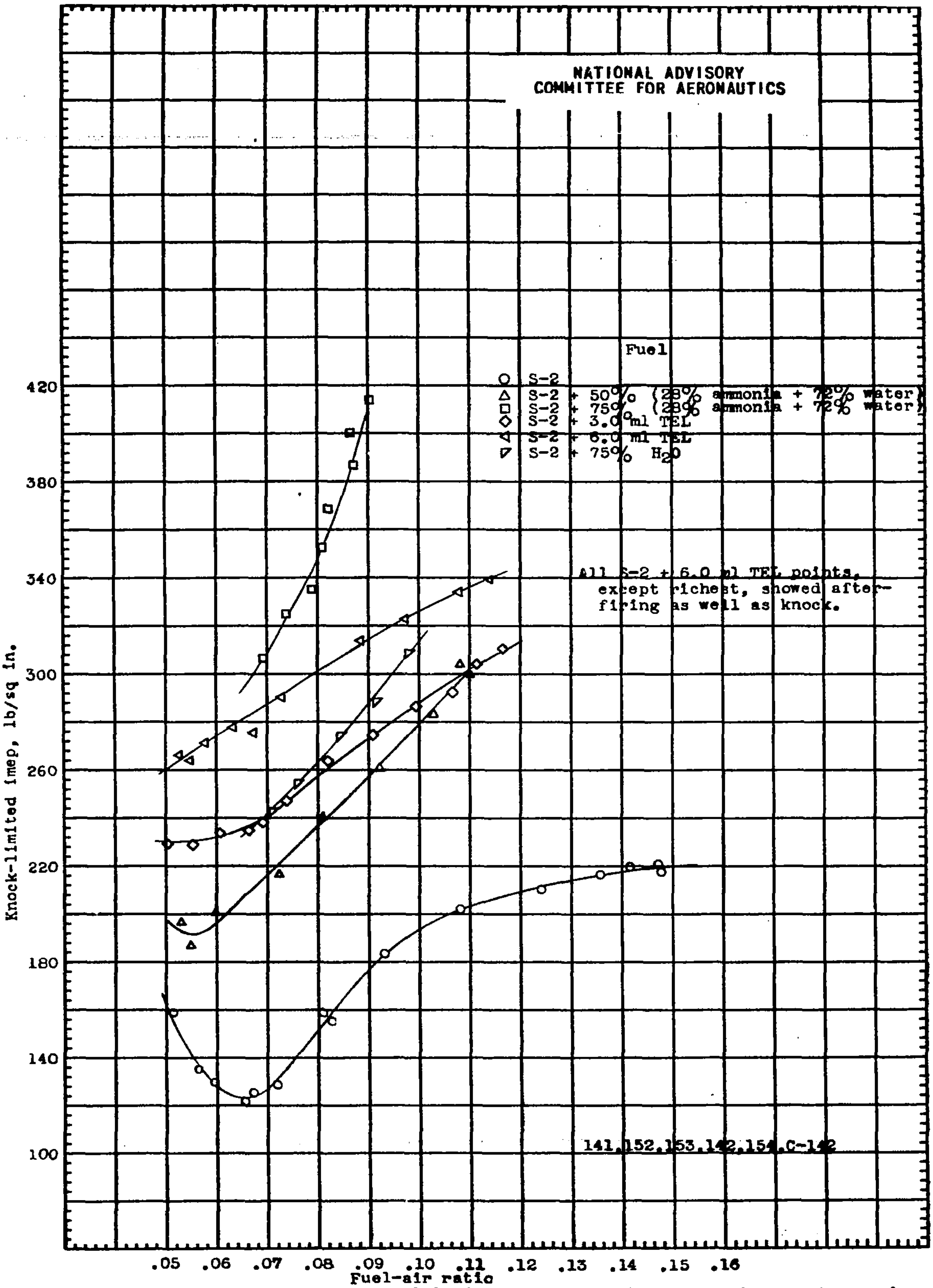

Figure 1. - Effect of addition of tetraethyl lead, water, or a mixture of 28 percent ammonia + 72 percent water on the knock-limited indicated mean effective pressure of S-2 reference fuel. Wright 1820 G200 cylinder; compression ratio, 7.0; engine speed, 2000 rpm; spark advance, 20° B.T.C.; inlet-air temperature, 250° F.

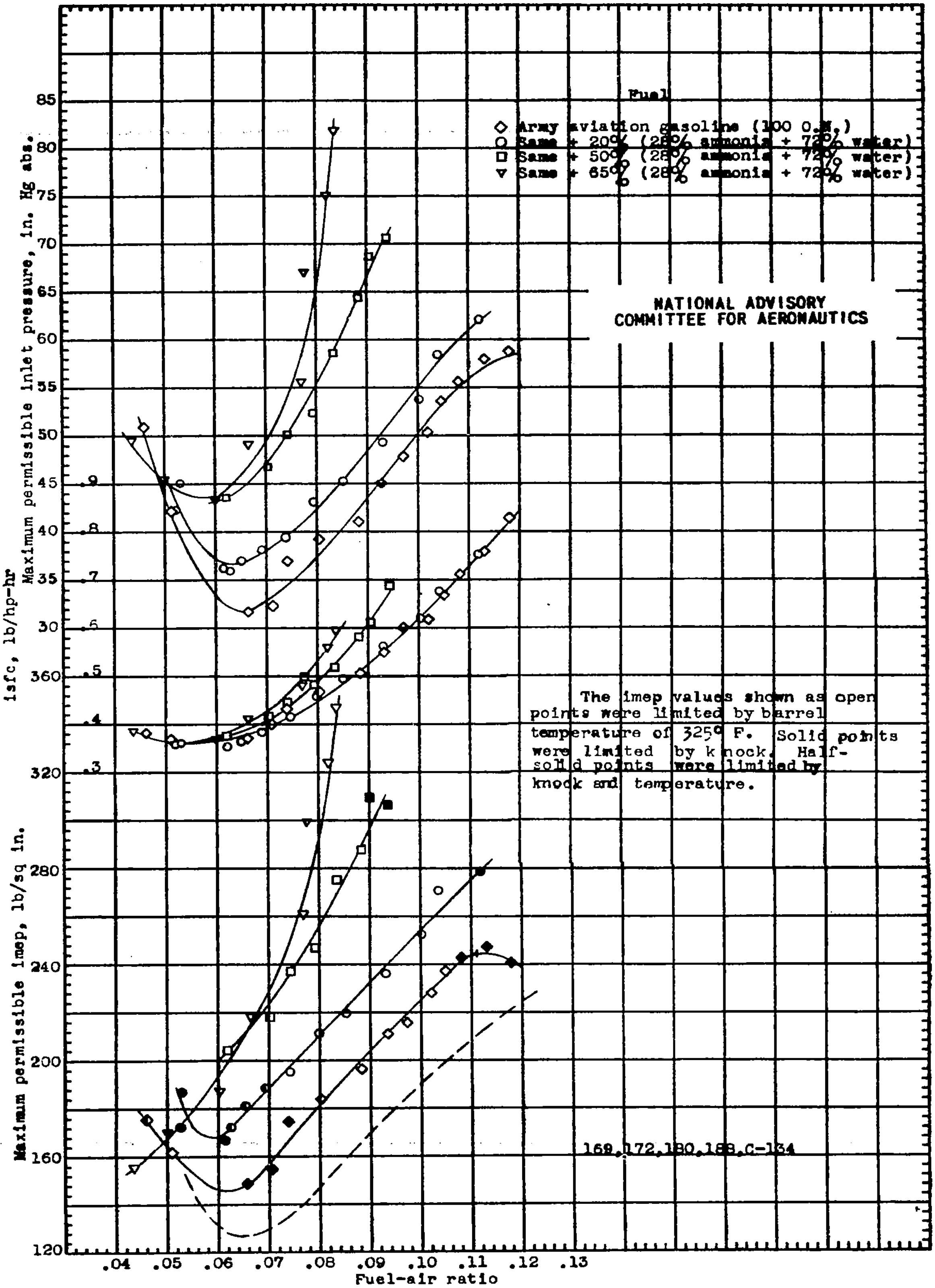

Figure 2. - Engine performance permitted by use of a mixture of 28 percent ammonia + 72 percent water as an internal coolant at a cooling-air pressure drop across cowling of 10 inches of water. Wright 1820 G200 cylinder; compression ratio, 7.0; engine speed, 2500 rpm; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air upstream temperature, 125° F.

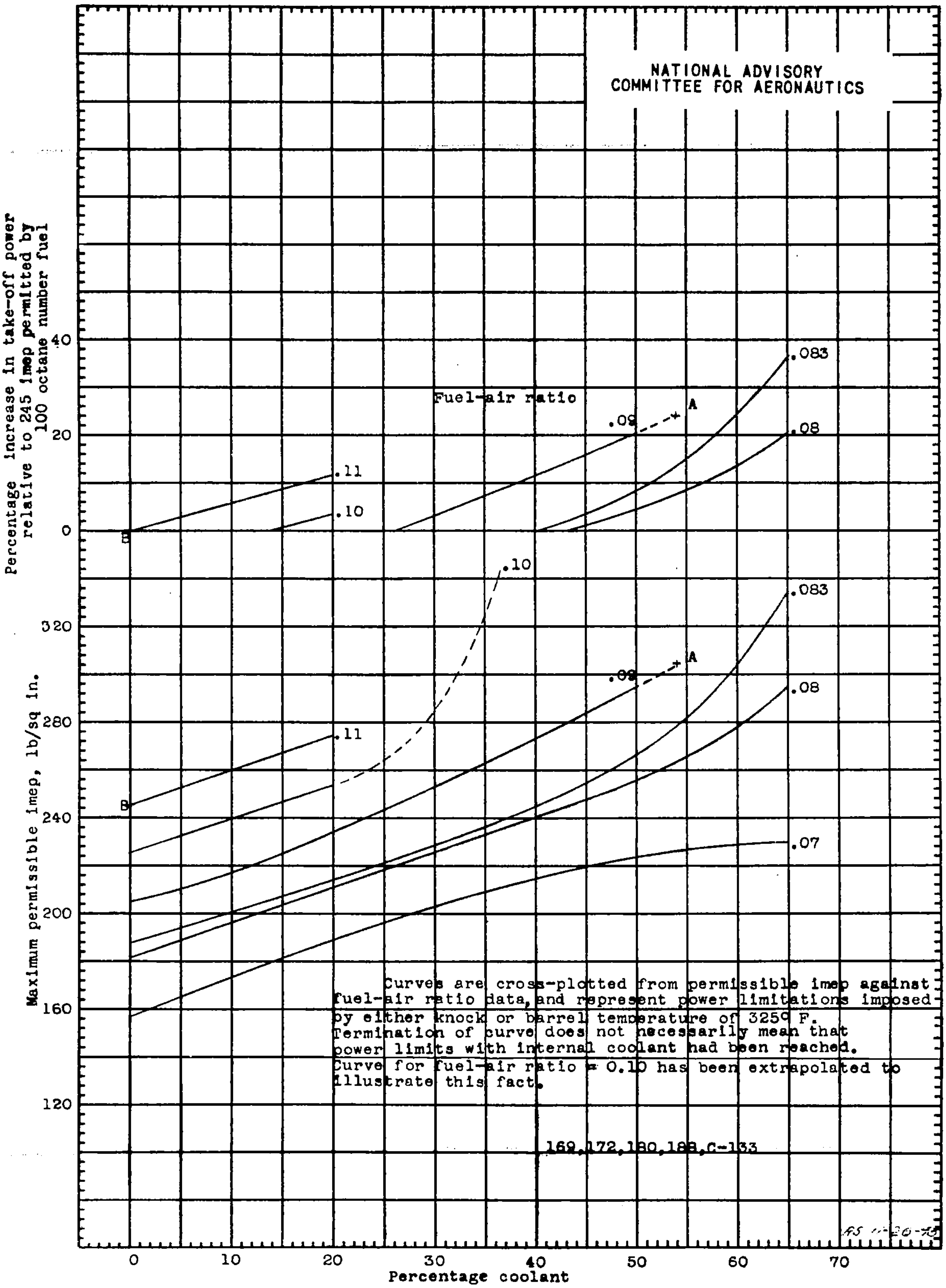

Figure 3. - Permissible power as determined by percentage internal coolant (referred to fuel weight supplied) at various fuel-air ratios and at a cooling-air pressure drop across cowling of 10 inches of water. Wright 1820 G200 cylinder; compression ratio, 7.0; engine speed, 2500 rpm; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air upstream temperature, 125° F; Army aviation gasoline (100 octane number); coolant 28 percent NH_3 + 72 percent H_2O.

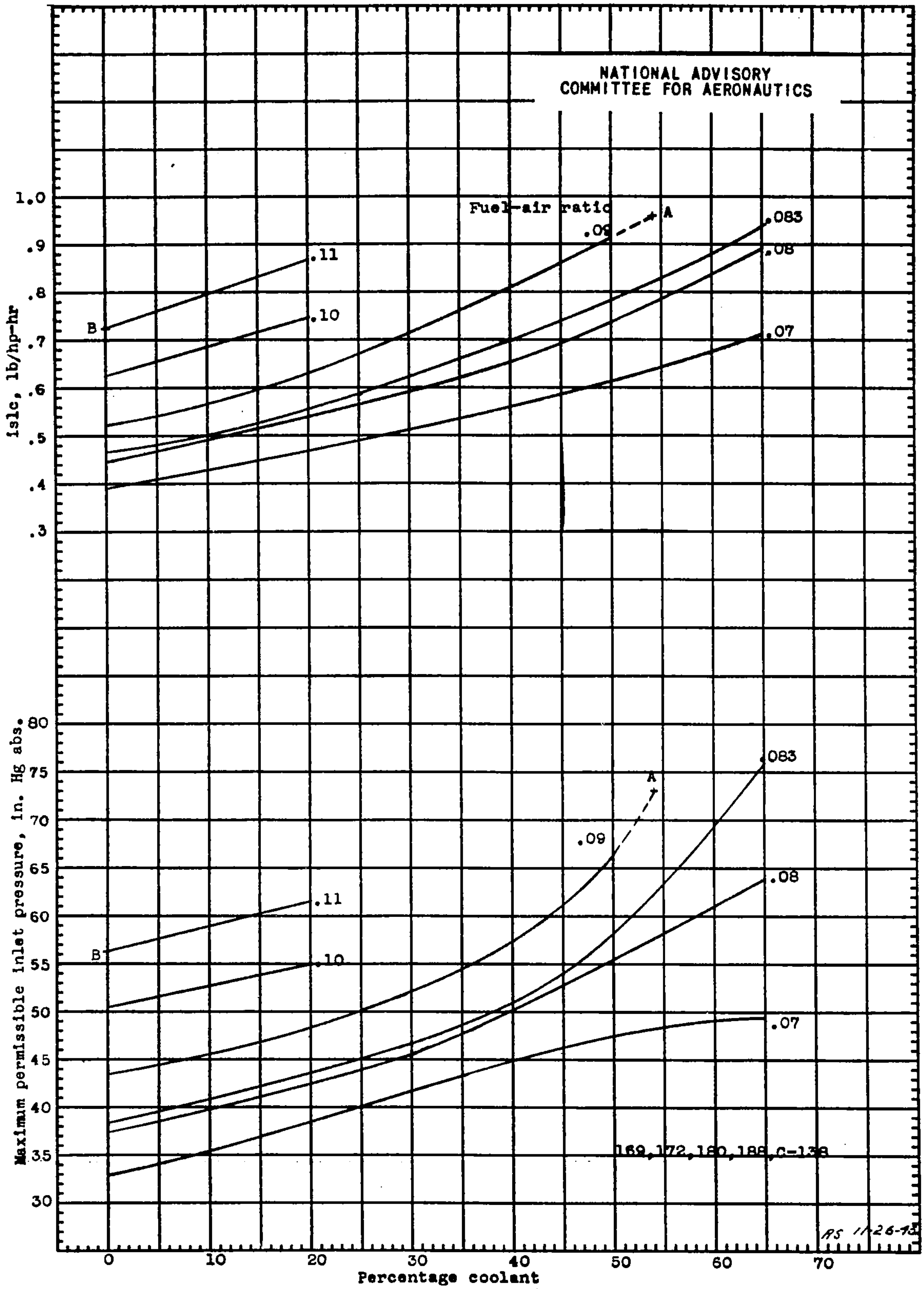

Figure 4. - Permissible inlet pressure and total liquid consumption as determined by percentage internal coolant at various fuel-air ratios and at a cooling-air pressure drop across cowling of 10 inches of water. Wright 1820 G200 cylinder; compression ratio, 7.0; engine speed, 2500 rpm; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air upstream temperature, 125° F; fuel, Army aviation gasoline (100 octane number); coolant, 28 percent NH_3 + 72 percent H_2O.

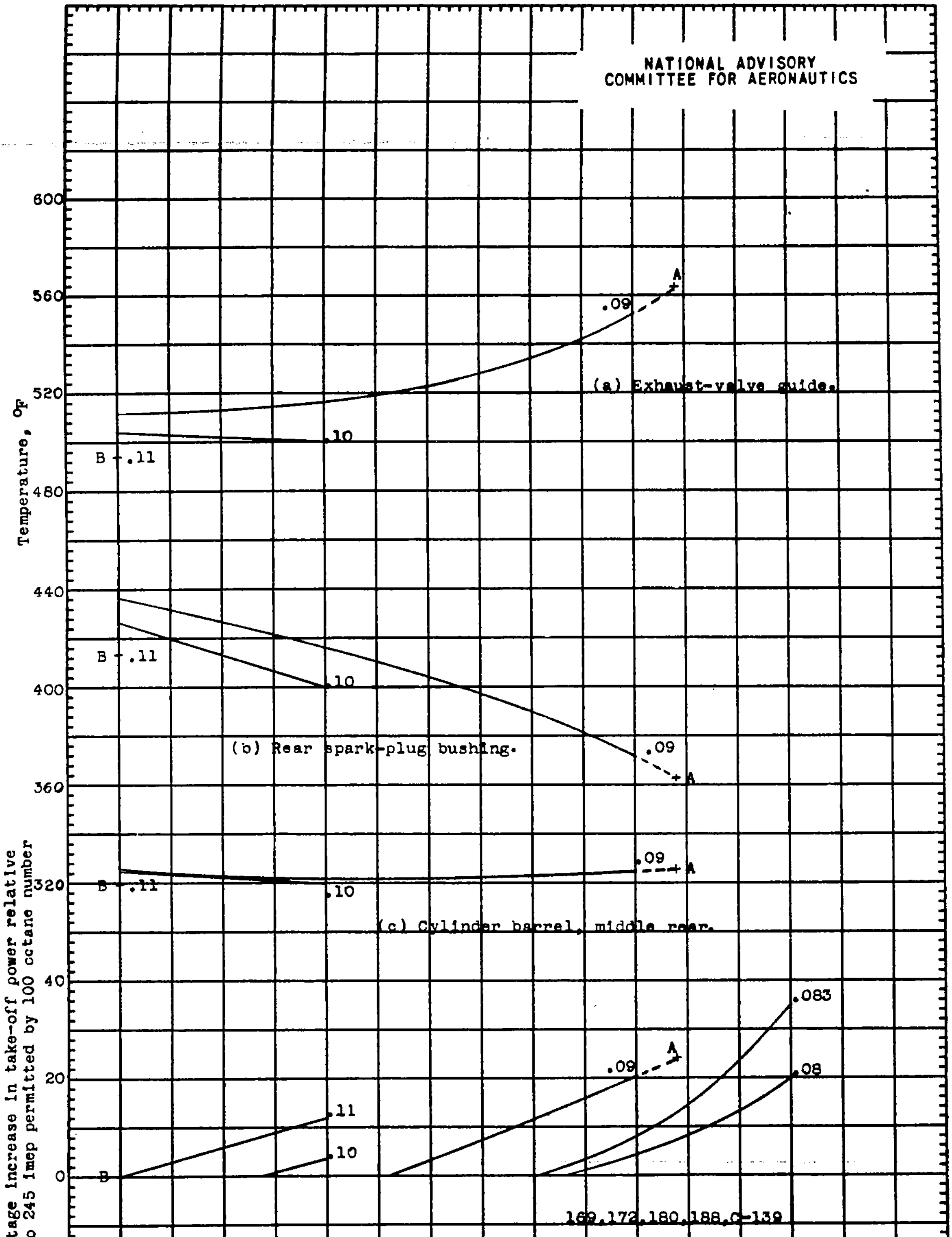

Figure 5. - Representative engine temperatures and percentage power increase (as determined by percentage internal coolant) at various fuel-air ratios and at a cooling-air pressure drop across cowling of 10 inches of water. Wright 1820 G200 cylinder; compression ratio, 7.0; engine speed, 2500 rpm; spark advance, 20° B.T.C.; inlet-air temperature, 250° F; cooling-air upstream temperature, 125° F; fuel, Army aviation gasoline (100 octane number).